

**AFRL-AFOSR-UK-TR-2011-0042**



## **Hall Effect Spintronics**

**Alexander Gerber**

**Tel Aviv University  
School of Physics and Astronomy  
Ramat Aviv  
Tel Aviv, Israel 69978**

**EOARD GRANT 10-3006**

**April 2011**

**Final Report for 15 January 2010 to 14 January 2011**

**Distribution Statement A: Approved for public release distribution is unlimited.**

**Air Force Research Laboratory  
Air Force Office of Scientific Research  
European Office of Aerospace Research and Development  
Unit 4515 Box 14, APO AE 09421**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY) 01-04-2011		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) 15 January 2010 – 14 January 2011	
4. TITLE AND SUBTITLE  Hall Effect Spintronics			5a. CONTRACT NUMBER FA8655-10-1-3006		
			5b. GRANT NUMBER Grant 10-3006		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)  Professor Alexander Gerber			5d. PROJECT NUMBER		
			5d. TASK NUMBER		
			5e. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Tel Aviv University School of Physics and Astronomy Ramat Aviv Tel Aviv, Israel 69978			8. PERFORMING ORGANIZATION REPORT NUMBER  N/A		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  EOARD Unit 4515 BOX 14 APO AE 09421			10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR/RSW (EOARD)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-UK-TR-2011-0042		
12. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>Following the original project continued research devoted to manufacture, study and optimization of materials suitable for spintronics applications based on the extraordinary Hall effect (EHE). The work was focused on three major tasks:</p> <ol style="list-style-type: none"> <li>1. Preparation and study of CoPd multilayers for the Extraordinary Hall Effect based magnetic memory.</li> <li>2. Development of a novel and effective experimental technique for determination of anisotropy constants in ultra-thin magnetic films with out-of-plane magnetic anisotropy.</li> <li>3. Search for magnetic reversal mechanisms stimulated by unpolarized electric current.</li> </ol> <p>This work produced the following three publications. A second grant commenced to continue this work under FA8655-11-1-3081.</p> <ol style="list-style-type: none"> <li>1. D. Rosenblatt, M. Karpovskii and A. Gerber, <i>Reversal of the Extraordinary Hall Effect polarity in thin Co-Pd multilayers.</i>, Appl. Phys. Lett., 96, 022512 (2010).</li> <li>2. D. Rosenblatt, M. Karpovskii and A. Gerber, <i>Monitoring magnetization reversal and perpendicular anisotropy of ferromagnetic films by the extraordinary Hall effect and anisotropic magnetoresistance.</i>, Jour. Appl. Phys. 108, 043924 (2010).</li> <li>3. O.Riss, A.Gerber, I.Ya.Korenblit, M.Karpovsky, S. Hachohen-Gourgy, A.Tsukernik, J.Tuailion-Combes, P. Melinon, and A.Perez, <i>Non-thermal magnetization reversal assisted by unpolarized current.</i>, Phys. Rev. B 82, 144417 (2010).</li> </ol>					
15. SUBJECT TERMS  EOARD, Hall effect spintronics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  SAR	18. NUMBER OF PAGES  7	19a. NAME OF RESPONSIBLE PERSON SCOTT DUDLEY, Lt Col, USAF
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)1895 616162

Department of Defense - DOD, U.S. AIR FORCE

**Grant No. FA8655-10-1-3006**

**Final Report**

(January 2010 – December 2010)

**Hall Effect Spintronics**

Alexander Gerber

School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel.

Following the original program we continued the research devoted to manufacture, study and optimization of materials suitable for spintronics applications based on the extraordinary Hall effect (EHE). The work was focused on three major tasks:

1. Preparation and study of CoPd multilayers for the Extraordinary Hall Effect based magnetic memory.
2. Development of a novel and effective experimental technique for determination of anisotropy constants in ultra-thin magnetic films with out-of-plane magnetic anisotropy.
3. Search for magnetic reversal mechanisms stimulated by unpolarized electric current.

### **1. Preparation and study of CoPd multilayers for the Extraordinary Hall Effect based magnetic memory.**

Thin Co/Pd multilayers, with room temperature perpendicular anisotropy and an enhanced surface scattering, were studied for the possible use in the extraordinary Hall effect (EHE) - based magnetic memory devices. Several parameters important for the room temperature applications of the EHE-based memory devices were found promising: EHE resistivity is of the order of  $0.5 \mu\Omega cm$ , which is equivalent to a difference of the order of  $1\Omega$  between the up- and down- magnetized states; coercive field depends linearly on a number of bilayers and can be tailored in the field range of 10 - 1000 Gauss. Polarity of the EHE signal was found to depend on thickness and time elapsed since the deposition. We argue that the effect is determined by surface scattering in thin and aged samples. It would be beneficial to find a proper matching in polarity of spin-orbital scattering within and at the surface of the selected material, while in Co/Pd multilayers studied here these polarities are opposite.

The work has been published in:

D. Rosenblatt, M. Karpovski and A. Gerber

*Reversal of the Extraordinary Hall Effect polarity in thin Co-Pd multilayers.*

Appl. Phys. Lett., 96, 022512 (2010).

## **2. Monitoring magnetization reversal and perpendicular anisotropy by the extraordinary Hall effect and anisotropic magnetoresistance.**

Ferromagnetic films with perpendicular magnetic anisotropy attract significant attention as strong candidates for realizing ultra-high density recording systems. For this, detailed information on the magnetization reversal mechanisms and determination of the magnetic anisotropy constants are particularly important. The magnetic anisotropy constants can be extracted from measurements of the out-of-plane component of magnetization by using the Stoner-Wohlfarth model [1]. The model is applicable for rotation of a single magnetic moment vector and is limited to the range of fields and angles at which rotation of magnetization is coherent in the entire sample.

We developed a novel technique by using two magnetotransport properties of ferromagnetic materials: the extraordinary Hall effect and anisotropic magnetoresistance to monitor the normal and in-plane projections of the magnetization in thin Co/Pd multilayers with perpendicular anisotropy. By reconstructing the normalized magnetization vector we were able to distinguish between the coherent rotation and domain nucleations during the process of magnetization reversal. Two experimental protocols were used: the traditional one which involves rotation of a magnetized sample and measurements in fields applied parallel to the film plane, and a new one, in which the entire experiment is performed under canted fields applied in a fixed orientation. We found that under fields canted beyond a certain critical angle the complete cycle of magnetization reversal takes place by a coherent rotation with an intermediate sharp flip-flop of the out-of-plane component. The range of applicability of the Stoner-Wohlfarth model is extended, and thus reliability of the extracted anisotropy constants is significantly improved when the measurements are performed under canted fields.

The work has been published in:

D. Rosenblatt, M. Karpovski and A. Gerber

*Monitoring magnetization reversal and perpendicular anisotropy of ferromagnetic films by the extraordinary Hall effect and anisotropic magnetoresistance.*

Jour. Appl. Phys. 108, 043924 (2010).

### 3. Search for non-thermal magnetization reversal assisted by unpolarized current.

Interplay between the spatial distribution of magnetic moments and electric current is the essence of the science of spintronics. Giant magnetoresistance (GMR) can be thought as the response of the current to a gradient of magnetization. The opposite effect: response of the magnetization to an electric current is now under scrutiny. Ferromagnets serve as spin filters for an electric current passing through the magnet: spin of the electrons that are transmitted through a ferromagnet becomes partially polarized parallel or antiparallel to the direction of the magnetization, whereas spin current perpendicular to the magnetization direction is absorbed. Spin filtering is the root cause for the spin-transfer torque, the phenomenon in which a polarized current impinging on a ferromagnet affects its magnetization direction. The spin-transfer torque gives rise to magnetization reversal and excitation of spin-waves in ferromagnet/normal-metal/ferromagnet trilayers (F/N/F) and domain wall motion in bulk ferromagnets and wires.

The original models of current induced spin wave excitation rely on exchange model of interaction between the itinerant electrons and the localized spins. It has been recently reported by I.Ya.Korenblit that in ferromagnetic conductors with large extraordinary Hall effect the relativistic electromagnetic interaction of the electron current with the field of the spin-wave can lead to current-induced spin-wave instability at critical *unpolarized* current of the same order or even smaller than that in the exchange interaction models. Unlike the exchange coupling of itinerant electrons with the spin-waves, which is effective only in the vicinity of the interface between normal and ferromagnetic layers, the above relativistic interaction acts also in the bulk of the ferromagnet. The mechanism proposed can be relevant for ferromagnetic films with an enhanced extraordinary Hall effect, like thin films of itinerant ferromagnets. In films with an out-of-plane magnetic anisotropy and magnetic moment oriented perpendicular to current direction the critical current of the instability is predicted to be in the range of  $10^5 - 10^7$  A/cm<sup>2</sup> which is much smaller than the critical current for spin-wave excitation with spin-transfer torques.

In this work we performed a systematic study of effects of temperature and current density on magnetization reversal of thin Ni films in a search of mechanisms not related

to spin polarization and Joule heating by passing current. Although heating is obviously present at high current densities, we identified a number of features inconsistent with the “thermal-only” mechanism: (i) the dependence of effective magnetic temperature on current density is significantly different from the known in art; (ii) the critical current density, beyond which the coercive field starts being dependent on current, increases with temperature despite of deterioration of cooling conditions; (iii) high enough current density was found to reduce the coercive field but not the value of the temperature dependent magnetization. The complex of these properties can be considered as an evidence of destabilization of magnetization by unpolarized electric current.

The work has been published in:

O.Riss, A.Gerber, I.Ya.Korenblit, M.Karpovsky, S. Hacohe-Gourgy, A.Tsukernik,  
J.Tuaillon-Combes, P. Melinon, and A.Perez

*Non-thermal magnetization reversal assisted by unpolarized current.*

Phys. Rev. B 82, 144417 (2010).